Variable pulse repetition frequency output from an optically injected solid state laser

D M Kane* and J P Toomey
MQ Photonics Research Centre, Department of Physics and Astronomy, Macquarie University, Sydney, NSW 2109, Australia
*deb.kane@mq.edu.au

Abstract: An optically injected solid state laser (OISSL) system is known to generate complex nonlinear dynamics within the parameter space of varying the injection strength of the master laser and the frequency detuning between the master and slave lasers. Here we show that within these complex nonlinear dynamics, a system which can be operated as a source of laser pulses with a pulse repetition frequency (prf) that can be continuously varied by a single control, is embedded. Generation of pulse repetition frequencies ranging from 200 kHz up to 4 MHz is shown to be achievable for an optically injected Nd:YVO₄ solid state laser system from analysis of prior experimental and simulation results. Generalizing this to other optically injected solid state laser systems, the upper bound on the repetition frequency is of order the relaxation oscillation frequency for the lasers. The system is discussed in the context of prf versatile laser systems more generally. Proposals are made for the next generation of OISSLs that will increase understanding of the variable pulse repetition frequency operation, and determine its practical limitations. Such variable prf laser systems; both low powered, and, higher powered systems achieved using one or more optical power amplifier stages; have many potential applications from interrogating resonance behaviors in microscale structures, through sensing and diagnostics, to laser processing.

OCIS codes: (140.0140) Lasers and laser optics; (140.3538) Lasers, pulsed; (140.3580) Lasers, solid-state; (140.3480) Lasers, diode-pumped; (190.3100) Instabilities and chaos.


1. Introduction

Lasers with pulse repetition frequencies between ~100 kHz to ~10 MHz are of particular interest for applications in laser processing that utilize pulsed-laser driven mechanical resonance effects to achieve a processing advantage [1]. Having prf-versatile laser systems, with a range of pulse durations, will service many applications in sensing, MEMS and biophotonics. We demonstrate that an optically injected solid-state-laser (OISSL) system is a potential new type of prf-versatile, pulsed laser system that does not obviously fit into any of the standard methods for achieving pulsed outputs. Prfs in the range 200kHz to 4 MHz are demonstrated in a Nd:YVO₄ OISSL. This research highlights that exploring nonlinear dynamics of laser systems as a source of "new" pulsed laser systems, and also to advance the detailed physical understanding of pulsed laser systems, is an approach worthy of further research effort. A brief introduction to existing prf-versatile pulsed laser systems that can provide prfs in the range of interest is given to facilitate comparing the new research on prf-versatile OISSL systems into a broader context.

Key characteristics of pulsed laser systems include pulse energy, pulse duration, pulse power, pulse repetition frequency (prf), and timing jitter specifications of several kinds. These characteristics, along with the lasing centre wavelength, determine the applications for which specific pulsed laser systems are suited. Gas lasers, solid state lasers, and semiconductor lasers are the three broad categories of lasers that are currently most used. The methods of achieving a continuous train of pulsed output from laser systems include gain switching, Q-switching, mode-locking, and self pulsation. Each broad category of laser can be operated pulsed by the four main pulsing methods. Gain switching and Q-switching are most appropriate for achieving variable prf in a controlled way.

In the case of pulsed gas lasers, the upper bound on prf, and therefore variable prf, is set by the kinetics of the gas discharge combined with the pulsed power supply technology used. Values of up to 4 kHz for excimer laser systems [2] and beyond 100 kHz for kinetically enhanced copper vapor lasers [3] have been achieved. Gas lasers cannot produce the high prfs sought.

Mode-locked solid-state-laser and fiber-laser based systems are a source of well controlled pulses with low timing jitter. However, mode-locked lasers generally have much higher prf which is usually single valued. It is set by the longitudinal mode spacing of the laser cavity [4, 5]. Typical prfs are from 50 MHz through to a few GHz [4].

1.1 Relevant semiconductor laser systems

Gain switched semiconductor lasers can provide pulses with repetition frequencies from below 1Hz to many GHz. Poor beam quality and timing jitter are the main reasons that semiconductor laser based systems for applications of the type we envisage have yet to emerge. Well controlled pulse streams can also be obtained from semiconductor lasers by self-pulsing [6–16]. The mechanism of self-pulsation was later understood to be as a result of saturable absorption (same principle as Q-switching) in the lasers. Self-pulsations due to saturable absorption effects have been investigated in stripe-geometry lasers [6–8], in two-section laser diodes [9,10], in multi-section distributed feedback (DFB) lasers [11–15] and in VCSELs [16]. In multi-section semiconductor lasers the self-pulsation can be controlled by varying the bias applied to the sections. The prf ranges achieved are typically 1 to a few GHz, but ranges of order 10 GHz [14, 15] with a maximum prf of 45GHz [15] have been achieved. Such GHz prfs are not our focus but the mechanisms of self-pulsation in semiconductor lasers are relevant to prf-versatile laser systems more generally.

1.2 Relevant Q-switched solid state laser systems

The systems with which the new prf-versatile optically injected solid state laser needs to be contrasted for producing versatile prfs in the 100 kHz to 10 MHz range are the Q-switched solid-state-lasers. It is Q-switched microchip laser systems, those using Nd:YVO₄ with its upper bound of 7.6 MHz prf as reported in [17], in particular, that are the main competition at...
this time. Modern Q-switched lasers, including passively Q-switched lasers, are primarily diode laser pumped solid state laser systems using semiconductor saturable absorber mirrors (SESAM’s), or variants thereof. Keller et al. reviewed the major advances, and underpinning laser physics, for these systems in [18]. The generation of pulses with durations below 1 ns, and even below 100 ps [17], has been achieved. Shorter pulses at higher energy have been the main aim in developing these systems. Pulse duration from 56 ps to 30 ns, and, repetition rates from 27 kHz up to 7 MHz have been achieved in 1.064 µm Nd:YVO$_4$ Q-switched microchip lasers by changing the design parameters of the saturable absorber and the pump power [19]. A prf range of 1-3 MHz was achieved using a semiconductor antiresonant Fabry–Perot saturable absorber (A-FPSA). The prf scaled approximately linearly with pump power as long as the absorber was fully saturated. The pulse duration was constant, ~3 ns. Similar results were obtained in a 1.34 µm Nd:YVO$_4$ [20] and a 1.062 µm Nd:LaSc$_3$(BO$_3$)$_4$ [21] Q-switched microchip laser. Pulse durations from 230 ps to 12 ns, and prf from 30 kHz to 4 MHz, have been achieved for Nd:YVO$_4$ by design changes [20]. For Nd:LaSc$_3$(BO$_3$)$_4$ pulse widths from 180 ps to 30 ns and repetition rates from 50 kHz to 7 MHz have been achieved [21]. Interestingly, a prf of ~7 MHz was obtained at lower pump powers and this scaled down to 400 kHz as the pump power increased, in a manner similar to some of the results that will be presented for the Nd:YVO$_4$ OISSL system with increasing injected power levels (reference [21], see Fig. 3(b), $R_t = 90\%$ trace). Similar dynamics, involving varying levels of saturation of an absorber may well be in play in both systems. The pulse duration reduced from 30 ns to 600 ps, scaling with the decrease in the repetition frequency (reference [21], see Fig. 3(a), $R_t = 90\%$ trace). These traces are in contrast with the standard models of Q-switched lasers.

Other non-SESAM-based, two-section, Q-switched microchip laser systems are common [22, 23]. A coupled-cavity, electro-optically Q-switched Nd:YVO$_4$ microchip laser achieved a pulse duration that scales linearly with the repetition frequency of the pulses (1.2 ns at 300 kHz to 8.8 ns at 2.25 MHz). The prf is determined by that of the electrical pulses (with a dc bias) applied to the LiTaO$_3$ EO-section for the purpose of changing the optical pathlength and hence the effective reflectance of the coupled cavity [22]. Prfs up to 2.25 MHz were achieved using a 440 µm long piece of Nd:YVO$_4$ (with 1.1-weight percent Nd) bonded to a 900 µm long piece of LiTaO$_3$. There are many reports of passively Q-switched laser systems using Nd:YAG (and variants with other dopants) as the gain section (eg [23]), but due to the longer upper level lifetime Nd:YAG based laser systems are not suitable for achieving MHz prfs. Upper limits of 70-80 kHz are more typical. But the system designs are relevant as they can be used in Nd:YVO$_4$ based lasers. Having established that Q-switched microchip laser systems and gain-switched semiconductor lasers should also be evaluated as potential systems for providing prfs of ~100 kHz to ~10 MHz in a continuously variable manner, we now introduce the Nd:YVO$_4$ OISSL system, and the new analysis of prior experimental and simulation results.

2. The Nd:YVO$_4$ OISSL system

The results analysed in this study have been the subject of prior publications and the experimental setup of the Nd:YVO$_4$ optically injected solid state laser (OISSL) system has been described fully in [24–27]. The Nd:YVO$_4$ OISSL system is shown schematically in Fig. 1.
Fig. 1. Experimental setup: LD, laser diode, 809 nm; FI, Faraday isolator; TEC, temperature control, sets frequency detuning; IF, interference filter, blocks 1064 nm pump transmission; BS, beam splitter; AOM, acousto-optic modulator, controls injected power; FP, Fabry-Pérot interferometer; PD, photodetectors; PD1 injection power, PD2 time varying output power, PD3 beat frequency between lasers. Figure reproduced from [24].

The relaxation oscillation frequency, $f_{RO}$, of the master laser was approximately 4.0 MHz. An optoelectronic feedback loop (not shown in Fig. 1) was used to suppress the relaxation oscillation peak of the master laser intensity noise spectrum [28]. The relaxation oscillation frequency of the slave laser was approximately 4.3 MHz. The maximum range of frequency detuning was approximately 32 MHz achieved by temperature control of the master laser crystal. The frequency detuning values appearing on graphs here-in are a dimensionless, normalized value $\Delta \omega$, which is multiplied by $f_{RO}$ for the slave laser to get the actual detuning frequency. The maximum detuning is very small compared to the longitudinal mode spacing for the laser (~76 GHz) so no mode hopping occurs. Two lasing modes can operate within the gain bandwidth for certain pumping conditions. For a fixed detuning, long time series data of the slave laser intensity were recorded as the injection strength ($K$) was slowly increased from zero until injection locking was achieved. This injection sweep was repeated at a large number of fixed frequency detuning values ($f_{RO} \times \Delta \omega$). The values of the injection strength are relative values that have been calibrated to the values at which the switch to injection locking was obtained from the model used to simulate the laser system [24, 25].

Previous studies have fully scoped the nonlinear dynamics of this system [24–27]. This also revealed parameter regions where the laser output power becomes pulsed [24, 25, 27]. It is shown that the repetition frequency of the pulses can be varied systematically by adjustment of the injection strength and/or frequency detuning between master and slave lasers.

3. Analysis, results and discussion

A total of 315 slave laser intensity time series were recorded during the experiment [26], each corresponding to a normalized frequency detuning value $\Delta \omega$ between −4.11 and 3.25 units. Each of these time series contain 883,000 data points of the laser intensity, sampled at 10 ns intervals, as the injection strength was swept from zero until the level at which the system reaches frequency locking of the slave to the master laser (CW injection locked output).

As was done in previous investigations [27], the long time series were divided up into 176 smaller subsets of 5000 points or 50 μs, giving a total of 55,440 subset time series to be analyzed. Since the total sweep time of the injection strength is on a much longer scale (approx. 9 ms), each subset corresponds to practically constant injection strength. The dominant frequency of each subset time series was determined automatically by identifying peaks (local maxima) and computing the average period. A map of the dominant frequency for all injection strengths and frequency detunings from $\Delta \omega = -4.1143$ to $+3.2551$ is shown in Fig. 2. The clear triangular section in the middle of the map is where the slave laser frequency is locked to that of the master and the slave has constant output intensity. The lower
frequency regions (those less than ~4 MHz) are where the laser output is clearly pulsed as
determined from the output power as a function of time. Outside of these regions the
dominant frequency corresponds to the laser relaxation oscillation frequency ($f_{RO}$) multiplied
by the frequency detuning ($\Delta \omega$). The relaxation oscillation frequency of the slave laser is $f_{RO} = 4.3 \text{ MHz}$.

Fig. 2. Dominant frequency from experimental intensity time series in the ($K$, $\Delta \omega$) plane.

At low injection strengths, particularly at larger magnitude frequency detunings, peaks in
the time series could not be accurately identified as their amplitude was comparable to the
noise level. This is the cause of the apparent frequency drop-off for low injection strengths
seen in the map in Fig. 2. The same map of the ($K$, $\Delta \omega$) plane with the z-axis rescaled to show
detail in the frequency range 0 to 4 MHz is shown in Fig. 3. It can be seen that the highest
frequency pulses appear within the 2 crescent shaped regions at $\Delta \omega = \pm (0.8 \text{ to } 2)$. For
negative detunings less than $\Delta \omega = -2$, once the injection strength is high enough to get the
laser into the pulsing region, the pulse repetition frequency decreases monotonically with
increasing injection strength.
To highlight the range of pulse repetition frequency attainable from this system, the prf as a function of the injection strength for fixed levels of detuning is shown in Fig. 4. The function shows piecewise regions where the prf varies continuously with injection strength. Full characterization of the system would be required to ensure that in practical applications regions where the prf shows scattered values are avoided. The injection strength acts as an easily modified control when implementing this system as a source of pulses with a frequency that can be varied in a continuous manner. The frequency detuning between master and slave lasers is a further control variable for accessing prf with a different functional dependence on injection strength. Smaller magnitude detunings allow access to the lowest values of prf but the rate of change of prf with injection strength is larger than at larger frequency detunings. Thus, larger magnitude detunings give a prf that is less sensitive to small variations in the injection strength. The accessible range of pulse repetition frequency is from approx. 200 kHz up to 4.2 MHz, as shown in Fig. 4. The form of the pulses at different prfs is shown in Fig. 5. The pulse duration, \( \tau_d \), has values between 22 ns and 53 ns in Fig. 5 with no clear systematic variations. Pulse durations as short as 10 ns occur within the complete data set.
In general the pulses at larger magnitude detunings are not as clean as those at smaller detunings. This is especially noticeable for injection strengths close to the injection locking boundary, where the pulses have much lower peak amplitude and contain several periods of the $f_\text{RO} \times \Delta \omega$ oscillations. Figure 6 shows a comparison of 1 MHz pulses from the system for small ($\Delta \omega = -0.74$, $K = 0.489$, Fig. 6(a)) and large ($\Delta \omega = -3.70$, $K = 3.190$, Fig. 6(b)) frequency detunings. It should also be noted that both the pulse amplitude and pulse spacing are quite varied in some regions of the $(K, \Delta \omega)$ parameter space. The pulse repetition frequencies shown in Figs. 2, 3 and 4 are an average frequency taken as the inverse of the average pulse period over the 50 $\mu$s time series. The standard deviation of the pulse intervals (as a percentage of the average pulse period) for all $(K, \Delta \omega)$ is shown in Fig. 7. This allows identification of preferred regions, where the standard deviation is small, and regions that should be avoided when robust single-valued prf is required. The two crescent shaped regions on either side of $\Delta \omega = 0$ at low magnitude negative detunings are where the most stable pulsing occurs. These correspond to the regions of the dynamical map bounded by period doubling bifurcations [24, 26]. The region just above the period doubling bifurcation boundary for negative detunings suggests that there are one or two more regions in the dynamic map that may not have been captured by the bifurcation analysis of the system [26]. The stability of the prf emerges as a new measurand with which to analyze the dynamics. These additional regions of high prf stability are in the vicinity of a saddle node and Hopf bifurcation according to the bifurcation analysis [24, 26].

Fig. 5. The range of pulse repetition frequencies which are accessible using this OISSL system.
(a) $f_{\text{pulse}} = 4.2$ MHz at $\Delta \omega = -1.94$, $K = 0.218$, $\tau_d = 49$ ns; (b) $f_{\text{pulse}} = 3$ MHz at $\Delta \omega = -1.31$, $K = 0.4$, $\tau_d = 45$ ns; (c) $f_{\text{pulse}} = 2$ MHz at $\Delta \omega = -1.02$, $K = 0.475$, $\tau_d = 31$ ns; (d) $f_{\text{pulse}} = 1$ MHz at $\Delta \omega = -0.74$, $K = 0.489$, $\tau_d = 45$ ns; (e) $f_{\text{pulse}} = 500$ kHz at $\Delta \omega = -0.95$, $K = 0.778$, $\tau_d = 22$ ns; and (f) $f_{\text{pulse}} = 200$ kHz at $\Delta \omega = -0.56$, $K = 0.394$, $\tau_d = 53$ ns.
Fig. 6. Comparison of 1 MHz pulses for (a) detuning $\Delta \omega = -0.74$ ($K = 0.489$, pulse envelope $100 \pm 5$ ns), and (b) detuning $\Delta \omega = -3.70$ ($K = 3.190$, pulse duration $42 \pm 2$ ns)

Fig. 7. Map showing the standard deviation in pulse period for all time series in the $(K, \Delta \omega)$ plane. Blue regions correspond to more stable pulses.

Comparison with simulated data has been completed. A single mode rate equation model of a class B laser, as described in [29, 30], was used to generate simulated output power time series for the parameter range covered in the experiments. The parameters used were identical to those used in [26]. Maps of the dominant frequency were generated from the simulated data in the same way as the experimental time series and are shown in Fig. 8 for (a) the full 0 to 16 MHz prf range and (b) limited to the 0 to 4 MHz prf range. These maps agree very well with Figs. 2 and 3 which show the experimental data on the same scales. The output power versus time graphs of the simulated time series themselves also have strong agreement, qualitatively, with those shown in Figs. 5 and 6 as demonstrated in prior publications [24, 25].
4. Prospects for practical PRF versatile OISSL systems

The average power of the Nd:YVO₄ OISSL system analysed is 8mW [24, 25]. This is lower than preferred for a laser system that is to be used for the range of applications envisaged. An average power of 350 mW has been reported in a Nd:YVO₄ Q-switched microchip laser system [17]. The output power can be amplified by of order 100 using available optical power amplification approaches [31–35], but it is nevertheless preferable that the base system should provide a higher output power. The system will also benefit from additional care and attention to the mechanical ruggedness of the laser heads, improved temperature control of the master and slave laser crystals, and possible improvements in the suppression of relaxation oscillations in the master laser [36, 37]. Thus, the next step in evaluating a practical prf versatile OISSL system should be to apply these improvements to a higher powered Nd:YVO₄ OISSL, to quantify the pulse duration and interpulse interval as a function of injection strength for steps in the frequency detuning and to also measure stability and timing jitter of the resulting pulsed output. Significant improvements in stability of the pulsed output in time for an OISSL system operating with a static system setting over that observed to date will be required of a system to be used in applications. It is anticipated these improvements will also be facilitated by a greater understanding of the OISSL dynamics.

To get additional and new insights into the mechanisms leading to the variable prf output of the OISSL system it will be fruitful to combine the approaches of nonlinear dynamics and standard laser rate equation analysis of the OISSL system. The rate equation model of the OISSL used to date [24] has given very good agreement with experiment provided a non-zero linewidth enhancement factor is introduced for the solid state laser gain medium. This is treating the Nd:YVO₄ as being similar to a semiconductor gain medium with a carrier density (inversion) dependent refractive index. This somewhat surprising requirement might now be reinterpreted as being equivalent to introducing a saturable absorber into the optically injected laser model. If the source of saturable absorption is identified and modelled appropriately, an OISSL model that will link more directly with the pulsed behaviours of the system may not require a non-zero linewidth enhancement factor. Possible sources of the saturable absorption are thermal lensing in Nd:YVO₄ [38] which in turn may alter the mode size of the lasing mode, dynamically altering its overlap with the pump mode and injection mode. Conroy et al. [39] have observed self-Q-switched operation in a Nd:YVO₄ microchip laser induced by refractive index related gain guiding and gain saturation effects. This required two longitudinal modes within the gain bandwidth of the microchip laser system as is the case for the Nd:YVO₄ OISSL system studied. Study of the transition from dominant quadratic index guiding to dominant gain guiding in determining the transverse-mode profiles for the output from a plano–concave Nd:YVO₄ microchip laser near threshold [40] is also a useful resource.
to incorporate in future models, when extended to include the dependence of the gain profile on the intensity profile of the lasing mode.

Finally, the upper limit on pulse repetition frequency observed in Q-switched Nd:YVO$_4$ microchip lasers is currently 7.6 MHz [17, 19]. In the OISSL system the upper limit to date is ~4.2 MHz, set by the highest power at which the master laser gave single frequency output. Extending this upper limit to higher frequencies will also be an aim. Using gain guided unstable cavity designs has successfully increased the cavity decay rate by a factor of ~3.5 in Nd:YAG lasers [41]. Thus, a Nd:YVO$_4$ Q-switched or OISSL system with a prf of up to 25 MHz is feasible once the physics of the gain is more fully understood and harnessed through laser engineering.

**Conclusion**

By adjusting the injection strength a Nd:YVO$_4$ optically injected solid state laser can be used to generate pulses with a continuously variable pulse repetition frequency. Frequency detuning between the free running optical frequencies of the master and slave laser is another parameter that can be used to access different ranges of prf, and different rates of change of prf with injection strength. Analysis of previously published experimental results from an OISSL system [24, 26, 27] demonstrates prfs between 200 kHz to 4.2 MHz are obtained. Pulse durations are between 10 and 100 ns. However, results from a system with improved mechanical and thermal stability, are needed to test the pulse duration and timing jitter specifications systematically and critically. Stability of the time period between pulses has been demonstrated as a new measurand of value for characterizing the nonlinear dynamics of a pulsed laser system. Future proposals for bringing the approaches of both standard laser physics and nonlinear dynamics in lasers to the pursuit of a prf-versatile Nd:YVO$_4$ OISSL producing prfs between 100kHz and 10 MHz (possibly 25 MHz) are introduced. Laser systems with this range of prf will have ready application in interrogating and driving resonance behaviors in microscale structures, sensing and diagnostics, and laser processing. Such a system may have some advantages over Nd:YVO$_4$ Q-switched microchip lasers. Its further study will be of value to laser physics, nonlinear dynamics and laser engineering.

**Acknowledgements**

This research was supported by the Australian Research Council, Arq Indigo Research and Development Ltd and Macquarie University: Linkage Project LP100100312. The experimental and simulation time series from the OISSL system, which underpin the analysis reported here-in, were generated by Simo Valling, Dr Thomas Fordell and Dr Asa Lindberg in the Department of Physics, University of Helsinki, Helsinki, Finland. We are grateful to Dr Lindberg and her group for sharing their experimental and simulation results with us and for discussions. We are also grateful to Professor Alan Shore and Dr Yanhua Hong, of the School of Electronic Engineering, Bangor University, Wales; and A/Prof Charles Harb, School of Electronic Engineering, University of New South Wales, Canberra, Australia; for discussions.
Optics Express

ISSN: 1094-4087
Title: Optics Express
Publishing Body: Optical Society of America
Country: United States
Status: Active
Start Year: 1997
Frequency: Bi-weekly
Document Type: Journal; Academic/Scholarly
Refereed: Yes
Abstracted/Indexed: Yes
Media: Online - full content
Language: Text in English
Price: Free (effective 2010)
Subject: PHYSICS - OPTICS
Dewey #: 621.36
LC#: QC350
CODEN: OPEXFF
Editor(s): Martijn de de Sterke (Editor-in-Chief), Sharon Jeffress (Managing Editor)
E-Mail: opex@osa.org
URL: http://www.opticsinfobase.org/oe/journal/oe/about.cfm

Description:
Covers original research in optical science and technology.

Additional Title Information
Alternate Title: Medline Abbreviated title: Opt Express

Request this title:
I’d like to request this title.
Corrections:
Submit corrections to Ulrich’s about this title.
Publisher of this title?
If yes, click GO! to contact Ulrich’s about updating your title listings in the Ulrich’s database.

Copyright © 2010 ProQuest LLC | Privacy Policy | Terms of Use | Contact Us